QUANTITATIVE CHARACTERIZATION OF THREE-DIMENSIONAL DAMAGE AS A FUNCTION OF COMPRESSIVE STRAINS IN AL 6061

Himanshu Agarwal[1], Arun M Gokhale[1], Mark F. Horstemeyer[2], Sam Graham[2]
[1]School of Materials Science and Engineering,
Georgia Institute of Technology, Atlanta, GA 30332-0405, U.S.A
[2] Sandia National laboratories, P.O. Box 969, Livermore, CA 94551-0969, U.S.A

Abstract

Al-Si-Mg base wrought alloys are widely used for automotive and aerospace structural applications, where mechanical properties are of central importance. Aluminum 6061 alloy is one of the alloy of this kind, which is widely used for structural applications. An extensive study on the damage evolution in Al 6061 alloy is performed at various strains under uniaxial compression. Digital image analysis techniques are used to study the three-dimensional damage at different strains. It has been found that the particle fracture is the main mechanism of damage in 6061 Al alloy under compressive loading.

Introduction

6XXX series of wrought Aluminum alloys are widely used in automotive and aerospace industries because of their good extrudability and excellent corrosion resistance. Aluminum 6061 is a typical alloy of this series that is widely used for structural applications. Failure of these alloys is caused by initiation and accumulation of microstructural damage. Microstructural damage is initiated by the formation of micro voids, which are formed by particle cracking and/or particle debonding. These micro-cracks grow, coalesce, and lead to final failure of the material. It is, therefore, necessary to study the microstructural damage as a function of strain under different loading conditions in order to understand the failure mechanisms. Microstructural damage can be quantitatively characterized by using standard stereological techniques. Such quantitative data are useful for the verification of theoretical models for damage evolution and fracture, as well as for the development of Finite Element based simulation models that can predict the mechanical response of these alloys.

It must be recognized that microstructural damage is of <u>three-dimensional</u> nature. In general, the relevant attributes of three-dimensional microstructural damage (for example, fraction of damaged particles, average volume of damaged particles, etc.) cannot be estimated from any measurements performed on random two-dimensional sections through a three-dimensional microstructure. Majority of the earlier studies on damage evolution are qualitative in nature. In the few quantitative investigations reported in the literature [1], characterization of microstructural damage has been performed only on random two-dimensional metallographic planes through the three-dimensional microstructural space, due to lack of suitable techniques for quantitative characterization of 3D damage. Consequently, there are no quantitative experimental data on three-dimensional damage initiation (due to particle cracking).

The objective of the present study is to quantitatively characterize the cracking of Fe-rich intermetallic particles in 6061 Aluminum alloy in three-dimensional microstructure as a function of compressive strain. It is concluded that a microstructure containing equiaxed (as opposed to elongated) fine particles is expected to be more resistant to damage initiation via particle cracking.

Experimental

<u>Materials</u>

The experiments were performed on the specimens drawn from extruded round bar (3.5" diameter) of 6061 Al-alloy in T651condition. The material was supplied by ALCOA. The chemical composition of the alloy is given in Table-I.

TABLE I Chemical Composition of Al 6061

Element	Zn	Ti	Si	Mn	Mg	Fe	Cu	Cr	Al
Wt pct	0.02	0.01	0.65	0.04	1.06	0.37	0.28	0.2	Balance

<u>Mechanical Tests</u>

Mechanical tests were performed on specimens extracted from the bar stock at a radial distance of 0.812'' from the bar center through EDM. This was done in order to assure that radial variations in material properties of the round bar did not influence testing results. All the specimens had their extrusion axis parallel to the applied load direction. These cylindrical cores were subsequently machined into smooth compression samples.

The uniaxial compression tests were run on an MTS81- Axial-Torsional servohydraulic test frame. Specimens were made in the form of cylinders that were 0.5 inches tall and 0.36 inches thick. Concentric grooves where machined into the ends of the compression cylinders in which a Mo based lubricant was placed. Lubrication was necessary in order to promote homogeneous deformation of the samples by lowering frictional effects at the sample ends. Samples were examined at the end of each test and no barreling effects were seen. Thus, homogeneous conditions are assumed for the compression tests. Quasi-static tests were run at strain rates of 2 x 10^{-4}/sec. These quasi-static tests were interrupted at different strain levels ranging from 3.75% to 70%. The uniaxial compression stress-strain curve is shown in Figure 1.

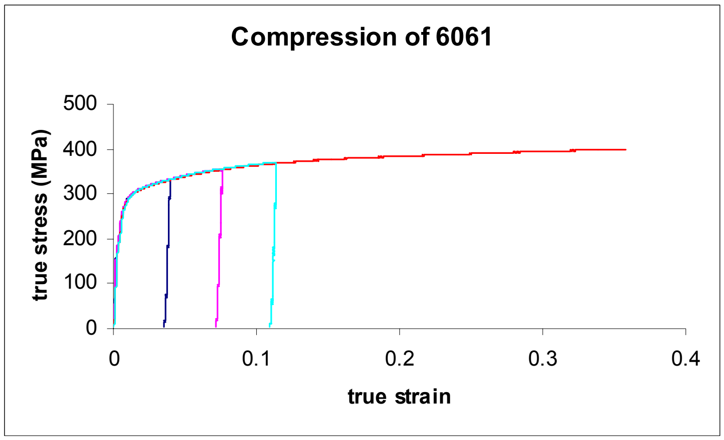

Figure 1: Stress-strain curve of Aluminum 6061 alloy in Compression testing

Metallography

The specimens were cut in the center along vertical planes containing the applied loading direction, which was also the extrusion direction of the extruded bar. The samples were mounted and then polished using standard metallography techniques [2]. The specimens were observed under optical microscope in unetched condition. Figure 2 shows the digital image microstructural montage of one of the specimens. The montage is a digitally compressed image, originally grabbed at 50X objective magnification (pixel size of 0.1973 microns). Observe that the microstructure contains two types of particles in the aluminum matrix. Light gray particles are Fe-based intermetallics, and dark particles are Mg_2Si intermetallics. Both type of particles are mostly oriented parallel to the extrusion axis, which is also the loading direction for all the specimens.
Failure of this material is associated with the microstructural damage, which is characterized by the nucleation, growth and coalescence of micro-voids. These micro-voids predominantly grow from cracked second phase inclusions/particles such as Fe-rich and Mg_2Si intermetallic particles. It has been qualitatively observed that damage due to cracking of Mg_2Si intermetallics is negligible in comparison to that due to Fe-based intermetallics. Therefore, in the present study, only fracture (cracking) of Fe based intermetallics has been quantitatively characterized.

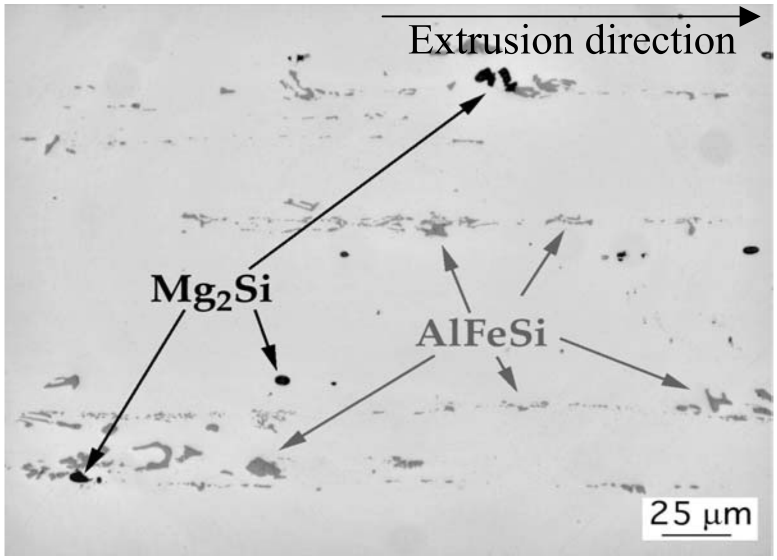

Figure 2: Optical Micrograph of 6061 Aluminum at 50X Objective

Quantitative Metallography

Number density, volume fraction, and total surface area per unit volume of cracked Fe-rich particles were measured at different compressive strain levels ranging from 3.75% to 70%. These measurements were performed on large number of contiguous fields (each 500X), typically, around 350-400 fields, to avoid edge effects in the damage quantification. All the measurements were averaged out over the entire specimen to eliminate radial gradients.

Volume fraction of the cracked Fe- rich particles was estimated by using standard stereological techniques [2]. As the microstructure is anisotropic, design-based stereological sampling is essential for unbiased and efficient estimation of the total surface are of damaged Fe-rich particles per unit volume of microstructure. This was carried out by using vertical sections technique that involves counting the number of intersections between particle boundaries and appropoately oriented <u>cycloid shaped test lines</u> [3,4]. In the present case, the microstructural anisotropy is symmetric with respect to the loading direction (which is also the extrusion axis), and therefore, such measurements on a single vertical plane containing the loading direction yield efficient and unbiased estimate of the three-dimensional total surface area of the damaged Fe-rich particles per unit volume, when loading direction is chosen as the vertical axis.

It is well-known that the three-dimensional number density of particles can not be estimated from measurements performed on random two-dimensional metallographic sections. The three-dimensional number density of particles in three-dimensional microstructure can be estimated in two ways: (1) by recreating the whole three-dimensional volume by taking series of two-dimensional sections and observing particles, or (2) by unbiased counting of particles in three-dimensions by using a pairs of planes at random locations, and following the disector principle [5,6]. The first approach is laborious, and it may not be practically feasible. The second approach (based on disector sampling) is efficient as well as unbiased. The second technique requires the unbiased statistical sampling of particles only from the pairs of montage serial sections. The unbiased technique for sampling particles in three dimensions is through use of disector approach. This technique makes no assumptions about the shape, size, and distribution of the features of interest. In this technique, sets of two parallel planes that are small distance apart are prepared, and then analyzed through the disector approach. The particles that appear in the first section but are not present in the second section are counted (let this number be Q^-). Similarly, the particles, which are not present in first plane, but are present in the second, are also counted (let this number be Q^+). The estimate of the number density of these features, N_V, is given by the following relationship:

$$N_V = \frac{Q^- + Q^+}{2At}$$

Where t is the distance between sections and A is the area of metallographic section.

In the present study, the three-dimensional number density of Fe-based intermetallics was estimated by using this approach. The distance between two consecutive planes was kept 1 micron (1/5th of the particle average Size). Three sets of disectors were analyzed to get the three-dimensional number density of intermetallic particles. First a montage of two-dimensional images was grabbed on the first metallographic plane. The specimen was then polished to remove 1-micron thickness of the material. The amount of material removed was controlled by monitoring the diagonal length of micro-harness diamond indents. A two-dimensional montage was then again grabbed on the second metallographic plane exactly at the same position as the first one. The exact position in the two planes was also identified by using the same micro-hardness diamond indents at all the corners of montage.

Results and Discussions

Figure 3 shows a plot of number fraction of broken/cracked Fe-rich particles observed in a metallographic plane (i.e., 2D damage), as well as number fraction of cracked/broken Fe-rich particles in three-dimensional microstructural space (i.e., 3D damage), as a function of strain under uniaxial compression strain. This plot shows that two-dimensional damage linearly increases with strain, whereas the three-dimensional damage appears to saturate at high strain levels. Observe that there are significant differences in 2D and 3D fraction of damaged particles at each strain level. The average volume (or average surface area) of cracked/broken Fe-rich particles can be calculated by dividing the volume fraction (or total surface area per unit volume) of the broken/cracked particles by their three-dimensional number density measured by using disector. Figure 4 and 5 show the variation of average volume (micron^3) and average surface area (micron^2) of cracked particles with strain, respectively. Observe that, both average volume and average surface area of cracked particles <u>increase monotonically</u> with strain under uniaxial compression. This implies that at higher strains, the particles of similar and/or larger size are getting fractured.

Particle shape factor can be defined as a ratio of [average volume]$^{2/3}$ and average surface area of particle. Figure 6 shows a plot of variation of cracked particle shape factor with strain in compression test specimens. The plot reveals that as the strain increases, cracked particle shape factor decreases, which means that elongated particles are more prone to fracture than equiaxed particles. Therefore, the increase in the number fraction of cracked/broken particles at higher strains is predominantly due to cracking of additional large elongated particles.

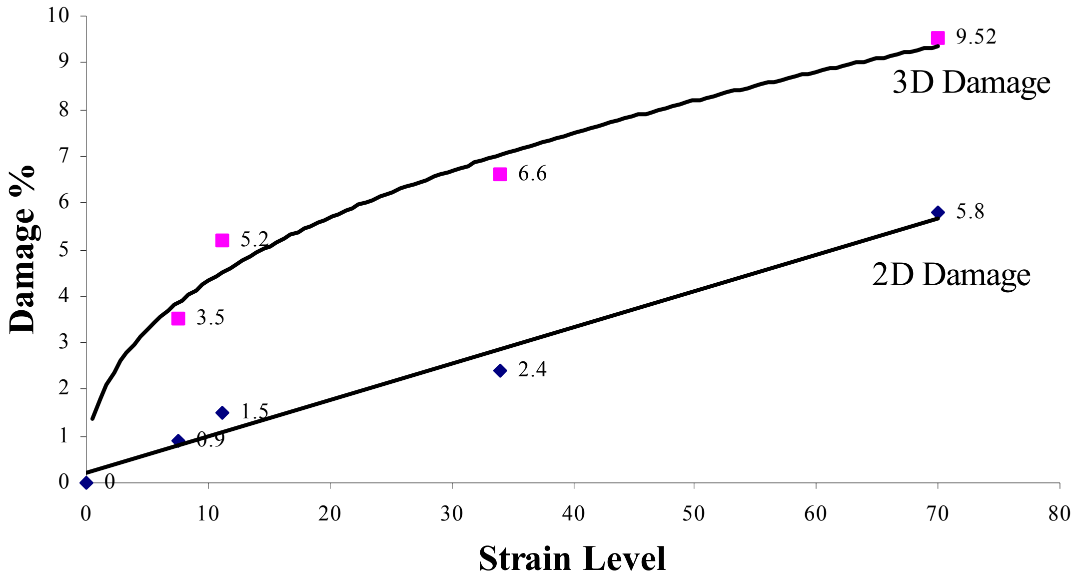

Figure 3 Comparison of 2D and 3D Damage as a function of Compressive Strain in Al 6061

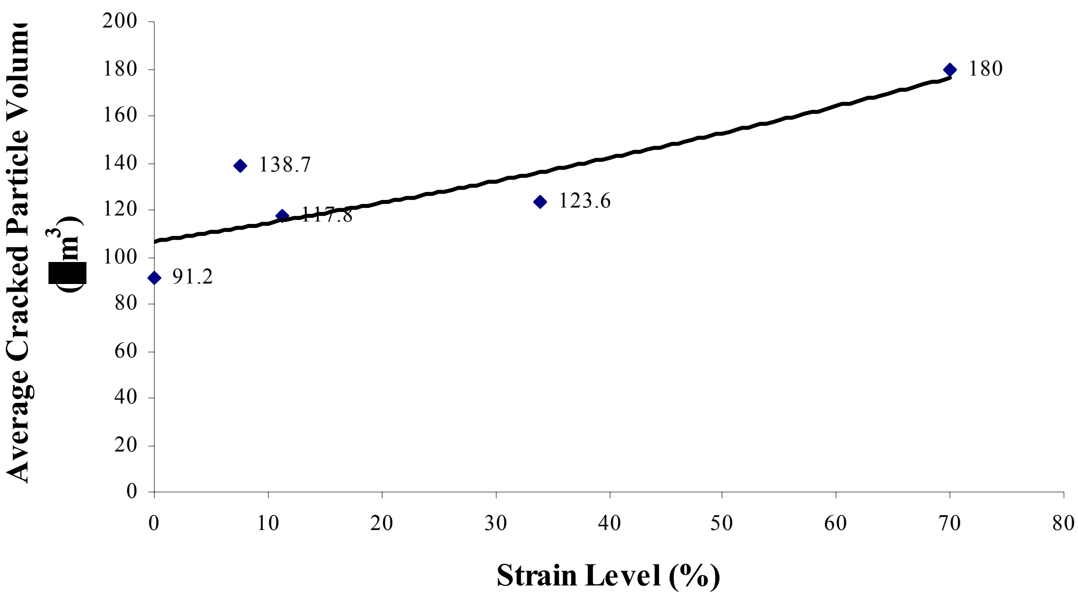

Figure 4 Average Cracked Particle Volume vs. Compressive Strain in Al 6061

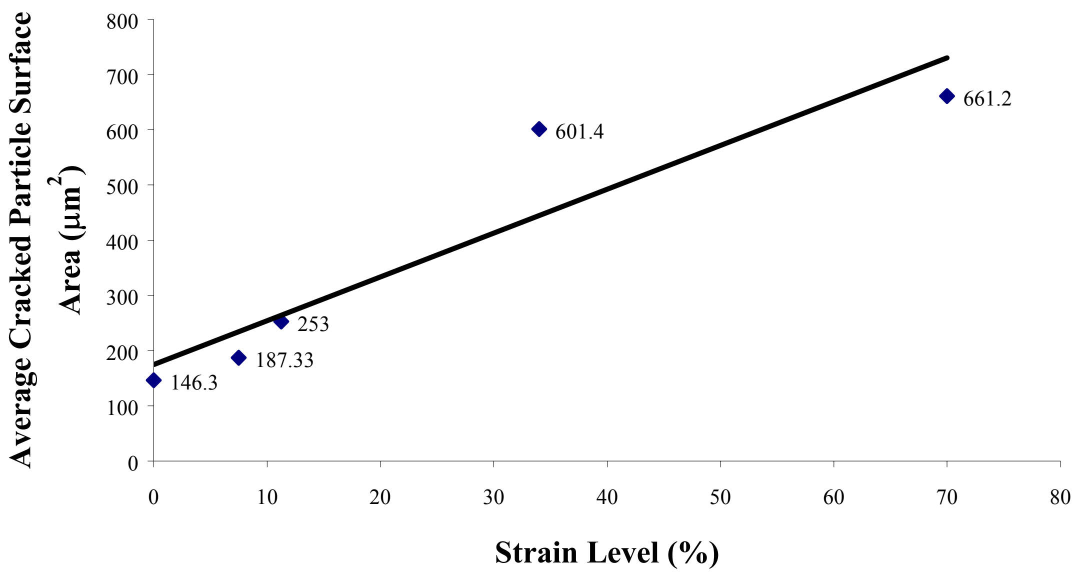

Figure 5: Average Cracked Particle Surface Area vs. Compressive Strain in Al 6061

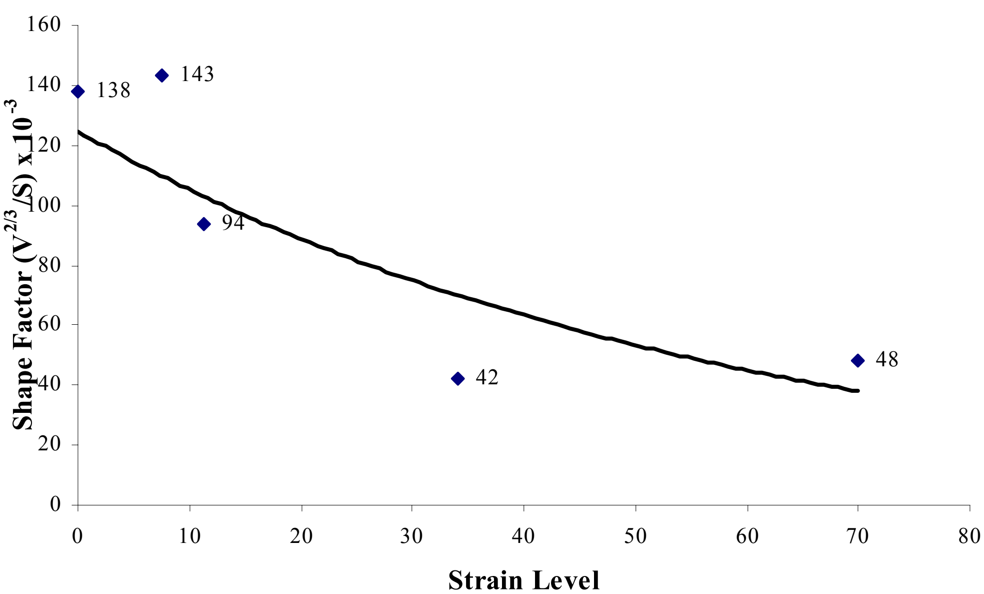

Figure 6: Cracked Particle Shape Factor vs. Compressive Strain in Al 6061

Summary

The three-dimensional microstructural damage in Al 6061 alloy is initiated by the formation of micro-voids, which are formed predominantly by the cracking of Fe-rich intermetallic particles. In the present study, the cracking of Fe-rich intermetallic particles has been quantitatively characterized in three-dimensional microstructure as a function of compressive strain. It has been shown that under compression, equiaxed finer particles are more resistant to damage initiation by particle cracking as compared to elongated larger particles.

Acknowledgements

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